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# Irrigating for Rainbows



by Jack Keller  
**61st Faculty Honor Lecture**

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## Sixty-first Honor Lecture Delivered at the University

A basic objective of the Faculty Association of Utah State University, in the words of its constitution, is:

to encourage intellectual growth and development of its members by sponsoring and arranging for the publication of two annual faculty research lectures in the fields of (1) the biological and exact sciences, including engineering, called the Annual Faculty Honor Lecture in the Natural Sciences; and (2) the humanities and social sciences, including education and business administration, called the Annual Faculty Honor Lecture in the Humanities.

The Administration of the University is sympathetic with these aims and shares, through the Scholarly Publications Committee, the costs of publishing and distributing these lectures.

Lecturers are chosen by a standing committee of the Faculty Association. Among the factors considered by the committee in choosing lecturers, are in the words of the constitution:

- (1) creative activity in the field of the proposed lecture;
- (2) publication of research through recognized channels in the field of the proposed lecture; (3) outstanding teaching over an extended period of years; (4) personal influence in developing the character of the students.

Jack Keller was selected by the committee to deliver the Annual Faculty Honor Lecture in the Sciences. On behalf of the members of the Association we are happy to present Professor Keller's paper.

*Committee on Faculty Honor Lecture*



# Irrigating for Rainbows

by  
Jack Keller

Quite simply, irrigation is the act of applying water to land. It is usually done to improve plant growth and it lies somewhere between an art, a science, and plain hard work. Even though we do not often think about it, irrigation is very important to the well-being of the world. It is important because we need basic foods to survive, and luxury foods and pleasant views to enjoy this survival. For the many people directly involved in irrigation, especially farmers, it provides a livelihood which is both satisfying and peaceful. And for the few of us lucky enough to be irrigation engineers, it is a love affair.

In the report which follows I will be discussing what interests me about irrigation: its extent and importance, its nature, some ecological aspects, the concept of design, energy and irrigation, and holistic thinking and innovative technologies.

Hubert Humphrey said: "In the long run, our food is our power— far more than our military power—and can be the critical factor in the achievement both of democratic institutions and of safety in the world. Food power is our secret weapon. Food is life. Food is strength. Food is hope and compassion. Food is the giver of health and vigor to children. Food is the vital ingredient of social stability and peaceful change. Let us use that power wisely and well."

## *Extent and Importance of Irrigation*

Living in a state like Utah, we all know that irrigation is widespread and important. The irrigation canals that traverse our valley provide water for the fields of corn and alfalfa, as well as for our beautiful landscapes and kitchen gardens. These canals also provide recreation in the form of fishing and tubing.

Table 1 gives estimates of irrigated acreage throughout the world. It may help put irrigation in Utah into perspective. Data for the mid 1980's reflect the long range national plans for development of the different regions. The target figures are sometimes unrealistically ambitious, and sometimes confuse what should be done and what can be done.

TABLE 1. *Areas of irrigated land in the world in millions of acres.*

Location	mid 1970's <sup>1</sup>	mid 1980's <sup>2</sup>	Targets <sup>2</sup>
<i>Developed Countries</i>	78.3	91	140
<i>Developing Countries</i>	224.3	264	498
Africa	5.4	7	28
Latin America	30.1	35	70
Near East	41.0	47	78
Far East	147.9	175	322
<i>Centrally Planned</i>	257.6	278	582
Asian C.P.	213.1		
Europe, USSR	44.5		
<i>World Total</i>	560.1	634	1220
<i>United States</i>	53.0 <sup>3</sup>	60.5 <sup>4</sup>	
<i>15 Leading States</i>	51.4 <sup>3</sup>	55.7 <sup>3</sup>	
<i>States</i> <i>Rank</i> <sup>3</sup>			
California	1	9.1	7.8
Texas	2	8.7	9.1
Nebraska	3	6.3	6.9
Idaho	4	4.1	4.9
Florida	7	2.8	4.1
Utah	10	1.9	2.6

<sup>1</sup>Taken from A. Aboukhaled, A. Felleke, D. Hiltel, and A. A. Moursi, *Opportunities for Increase of World Food Production* (Report to the Technical Advisory Committee of the Consultative Group on International Agricultural Research, I.D.R.C., Ottawa, Canada, April 1979), p. 161.

<sup>2</sup>Taken from J. Doorenbos, "The Role of Irrigation in Food Production," *Agriculture and Environment* 2(1975):39-54.

<sup>3</sup>Taken from Dick Morey, "Crystal Balling the Irrigation Industry," *Irrigation Journal* (March/April 1977):6-7.

<sup>4</sup>Personal estimate based on Morey's estimate in "Crystal Balling the Irrigation Industry."

Dividing the irrigated areas by population indicates that if the world's 560 million irrigated acres were equally divided among all the people, each person would have about an 80- by 80-foot plot. With high yielding varieties of grain and adequate fertility such a plot is large enough to provide an adult with a subsistence diet. The estimated 53 million irrigated acres in the United States could provide each American with about a 105- by 105-foot plot. Utah's 1.9 million acres is enough for each of us to have about a 260- by 260-foot irrigated garden. (That is big enough to grow a lot of zucchini!)

Effective irrigation pays large dividends in terms of yields in the developing countries. According to Peterson<sup>1</sup> while only 12.9 percent of the total cropped area of the world is irrigated, it produces 34 percent of the crop value. In the Middle East 68 percent of the crop value is obtained from the 24 percent which is irrigated. In Asia 40 percent of the crop value is obtained from the 24 percent which is irrigated. According to Wellhausen<sup>2</sup> over half of the crop value in Mexico is produced by the 30 percent which is irrigated. The 1974 Census of Agriculture showed that only 12 percent of the United States farmland was irrigated, but it accounted for 37 percent of the value of all crops sold. In addition, it showed that 63 percent of the orchard land and 52 percent of the acres of all vegetables harvested for sale in the U.S.A. are irrigated. In summary, the estimated 560 million acres of irrigated land in the world is about 15 percent of cultivated land and various estimates suggest that it produces between 30 and 50 percent of the crop value.

Agriculture is usually a gamble. Modern agriculture with pest protection, supplementary irrigation and technological know-how makes it less so. Perhaps the most profitable irrigation system is one which is on standby in a relatively humid area. It gives the assurance that moisture will not be a limiting factor—so the farmer can add the needed inputs for optimum yields. If the rainfall is sufficient, he gets optimum yields without the expense of operating his irrigation system. If it is a dry year, he irrigates to get optimum yields and take advantage of his other input such as tillage, seed and fertilizer.

<sup>1</sup>D.F. Peterson, "Hydrology, Water Management and Productivity," paper presented at AAAS Annual Meeting, New York City, January 26-31, 1975.

<sup>2</sup>E.J. Wellhausen, "The Agriculture of Mexico," *Scientific American* 235(September 1976): 129-150.

On a large portion of the rainfed cropped land if irrigation is available, two crops can be raised instead of one crop per year. This, plus the added and more certain productivity of irrigated land, is why irrigation is so important for stabilizing and expanding the world's supply of food.

So far irrigation has often been considered mainly as a means to bridge annual drought periods and to water desert lands, especially where agricultural production is based almost exclusively on irrigation, as in Egypt, Jordan and Saudi Arabia. Since variability in weather and climate is becoming an increasingly important factor in influencing national and regional food situations, it is recognized that extending the area with an assured water supply has become particularly urgent. Through modern technology, irrigation can be seen to stabilize and increase agricultural production. Countries like Afghanistan and Lebanon have adopted dual programs in order to cover both rainfed and irrigated agriculture. But irrigation can do more; it permits optimum utilization of fertilizers, the introduction of highly responsive seeds, and advanced tillage techniques and practices. The lack of an assured water supply has been one of the main bottlenecks in the successful introduction of high yielding varieties. Irrigation has thus become an input of agricultural production and, where natural conditions are unfavorable, the most important one. Investment in irrigation work must therefore be regarded as basic to agricultural development and, consequently, to long term goals for social and economic development.

### *Nature of Irrigation Systems*

Irrigation involves the two broad categories of resources: natural (including physical and biological) and social. The physical resources are very large but ultimately fixed. They are the four basic elements of the Greeks: earth, air, fire, and water. (Our modern metaphor for fire is work or energy.) The biological resources, on the other hand, cannot be assigned dimensions or limits. They include the plants and animals farmers grow plus the micro- and larger organisms that play essential and diverse roles in the food system.

The social resources are also essential to irrigation and are basically unbounded. They include the capital for irrigated agricultural development, social institutions that help farmers do



their job, human labor and skills, and the growing store of scientific and practical knowledge that has transformed irrigated agriculture in the past and can be counted on for even greater changes in the future.

The anatomy of an irrigation scheme may consist of gigantic dams to impound and store water, large pumping plants and extensive canal or pipe systems to distribute water to the fields, and elaborate mechanized irrigation systems to apply the water to the land; or it may merely be a farm pond and a bucket. But irrigation is a happening that requires an irrigator and the development necessary to supply water to the field and service the irrigation system.

Thus, a functioning irrigation system is first of all a mental image which consists of the irrigator, his tools (requiring capital) and labor. An endless number of tradeoffs can be made between management, labor, capital and energy inputs; and through man's inventive genius numerous irrigation techniques have evolved.

The traditional method of irrigating by directing natural or controlled streams of water to the cropped area through basins or furrows has been practiced for about 5000 years. This method is called gravity or flood irrigation. It relies on the mental image in the mind of the irrigator plus his energy and skill in performing his art; the only tool involved may be a simple shovel-like implement. The irrigator's job requires deciding when and how much to irrigate (scheduling), planning how to move the water around, plus physically coaxing it as uniformly as possible over the area being irrigated.

In contrast to the traditional irrigation system, there are completely automatic systems where the irrigator's job becomes: deciding when to punch the start and stop buttons (scheduling the irrigations); keeping energy supplied to the pump and drive systems; and servicing and maintaining the machinery and equipment. A professional service can be employed to make the scheduling decisions or the farmer can rely entirely on moisture sensing instruments to turn the system on and off. By mechanizing the system, the mental images and management skills of the inventor, engineer and technicians who designed and installed it are transferred to the farmer through the irrigation hardware. Obviously, an irrigator with a mechanical system can handle a larger area, perhaps as much as 1000 times more, than an irri-

gator with a traditional system. But when the army of people involved in the manufacture, sales, service and energy supply network for the mechanized system are included, the numerical contrast is much less impressive.

Major advantages of mechanical systems over traditional systems include: ease of management; reduced labor requirements, less drudgery; less irrigation skill to operate efficiently, and more precise water application. Furthermore, mechanized systems can be made to operate effectively in sandy and hilly lands that are impractical to irrigate by traditional methods. Thus, through innovative irrigation tools, we are able to expand our capacity to produce food. For example, center-pivot sprinklers, that can provide daily irrigations, have reduced the need for the soil to hold water and have made the sand hills of the Midwest into a major corn producing region; and trickle irrigation which can be used on almost any terrain, has made the 50 to 60 percent mountain slopes in San Diego County into prime avocado growing areas.

Center pivot systems are the most extensively used fully-automatic irrigation tools and to me the most fascinating. They travel in a circle and irrigate large areas up to one-mile in diameter covering 500 acres. They can operate continuously without interruption or attention because the circular path has no end. Center-pivot irrigation is nicely described by Splinter<sup>3</sup> in *Scientific American*.

A center-pivot system consists of a row of sprinklers mounted on a pipe that is in turn supported over the crop by mobile towers. Water is pumped into the pipe from a source at the center of the field, and the towers which are mounted on wheels carry the pipe around the fixed pivot point. The rate at which the towers and pipe advance is set by the speed of the outer-most tower, and alignment devices at each inner tower detect any laggards and move each tower to line up with the one beyond it. Thus an advance by the outermost tower sets off a chain reaction of advances beginning with the second tower from the outer end and progressing toward the center of the circle.

The mental image of the center-pivot technique was first envisioned about 30 years ago by Frank Zybach. He developed his

<sup>3</sup>W.E.Splinter, "Center-Pivot Irrigation," *Scientific American* 234(June 1976):90-99.

machine while farming in Colorado near Strasburg, east of Denver. After many trials and adjustments, the machine was first made to work and a U.S. patent was granted in 1952. The first crude commercial center-pivot systems were introduced a year later. Over the intervening years the machine has been perfected by engineers and craftsmen with mechanical skills and irrigation expertise. Irrigation engineers tailor the center-pivot for a given site. Today there are over 80 thousand center-pivots (they make those green circular fields that space travelers comment about) irrigating some 10 million acres throughout the world. Approximately 70 thousand center-pivots are in the United States and 10 thousand are in the Soviet Union.

Trickle irrigation (I don't like being called a drip engineer) is another ingenious innovation that can be fully automated and used under adverse land and water conditions. Shoji<sup>4</sup> presented an interesting commentary on trickle irrigation in *Scientific American*. He credited Symcha Blass, an Israeli engineer, with being the first to visualize trickle irrigation. More than 40 years ago Blass observed that a large tree near a leaking faucet exhibited a more vigorous growth than the other trees in the area which were irrigated by conventional means. The example of the leaking faucet led him to the concept of a system that would apply water in small amounts, literally, drop by drop. He devised and patented a low-pressure system for achieving this. The system consists of small diameter tubing laid on the surface of the field alongside the plants. Water is delivered to the plants slowly but frequently from holes or special emitters located at appropriate points along the tubes.

When Blass conceived the concept, now called trickle or drip irrigation, the plastic materials which are now used to build reasonably inexpensive systems were not available. By the 1950's the plastics industry had developed sufficiently to produce economical, flexible tubes and emission devices. The earliest trickle systems consisted of emitters made of tiny 4/100-inch diameter capillary tubes that restricted the flow to a trickle. The emitters were attached to networks of 1/2-inch diameter hose. This basic concept is in use today. However, more elaborate emitters, some of which have the ability to regulate their own

<sup>4</sup>K. Shoji, "Drip Irrigation," *Scientific American* 237(May 1977):62-68.

discharge and/or automatically flush themselves, very small spray emitters, and tubing which incorporates both the carrier pipe and emitter functions in a continuous line are now available. In addition, automatic valving and better water treatment facilities (reducing the hazards associated with clogging the emitters' openings) have also been perfected.

Commercial trickle irrigation began in the mid 1960's. Shoji estimates that there are almost 900 thousand acres of trickle irrigation in the world today—with 100 thousand of them in California. This rapid growth attests to its advantages. Since trickle irrigation slowly and frequently supplies precise amounts of water, the soil-water content in the plant root zone remains relatively constant; hence the plants grow without water stress in an environment of favorable moisture. This results in fast uniform growth and high yields.

Another advantage of trickle irrigation is its ability to make maximum beneficial use of available water. With trickle irrigation the parts of the field that are between the rows of plants remain dry so that little water is lost to evaporation, runoff, wind drift, or deep percolation. Plants use as much water as with other methods, but with trickle irrigation, losses are minimized. The result is irrigation efficiencies from 80 to 95 percent as compared with 60 to 85 percent for sprinkle irrigation and 40 to 80 percent for surface irrigation. A third major benefit from trickle irrigation is that it works well even if the water is quite saline because it does not wet the leaves, and the frequent irrigations and favorable moisture environment in the root zone keep the salt concentration low. Additional advantages are that the system is adaptable to almost any soil type or terrain and it can be automated.

### *Some Ecological Aspects*

Solving the questions concerning the interactions between society and nature while providing food for the evergrowing population of our planet is one of the most pressing problems today. Increasing food production calls for the use of more land, larger amounts of water, pesticides, fertilizers, and energy. Growth of food production is intimately associated with the use of major natural resources and changes in the human environment and living standards.

Zonn<sup>5</sup> has pointed out that a keen interest in the environment is not accidental. It first emerged because man, while cultivating lands, affected it more and more, deliberately contributing to changes in historically settled ecological relations. Extension of agricultural areas, advances in land reclamation, including irrigation, resulted in replacement of natural ecosystems in many regions on our planet by artificial ones, i.e., those created and maintained by human agricultural activity. Irrigation, being one of the important means for intensifying agricultural production, has been used from ancient times to provide the most favorable conditions for obtaining stable production of high quality.

When developing irrigation projects and systems, people often believed (and still do) that two leading components of the natural environment, earth and water, are practically inexhaustible and hence their use needs no controls or regulation. Negative consequences of their uncontrolled exploitations are well known. Since irrigation is related first of all to construction of irrigation systems and then to modifying the "water-soil-plant-atmosphere" system, it produces a very important impact on the biophysical environment. From an ecological viewpoint, irrigation can be described as an engineering practice by which man influences the natural conditions. I should also point out that irrigation not only affects the natural environment, but also leads to change in the social and economic structures of society.

Along with the impressive achievements in irrigated agriculture (higher soil productivity and increased agricultural production), irrigation has caused, from early times, some negative effects, unforeseen or unaccounted in design, construction and land cultivation. While the positive effects of water exploitation are encountered every day, the negative effects are less visible until they emerge as a real problem. Most of them, such as salinity, waterlogging, soil erosion, floods and water-borne disease, are not new but may reach new dimensions as a result of the increased speed at which water and land development is taking place. Without denying the need to pursue ecological studies and to gather additional knowledge about the environment, there is an evident risk, if, for the sake of more

<sup>5</sup>I.S. Zonn, "Ecological Aspects of Irrigated Agriculture," *ICID Bulletin* 28,2(1979):27-32.



accurate scientific knowledge, the solution to those problems is postponed until the damage is irreversible. For instance, in many cases a drainage system should be regarded as an integral part of the irrigation project. This basic requirement, because of its high cost is often deferred purposely until new data are available or until soil salinity and waterlogging make drainage indispensable.

A project should not be planned in isolation. Consideration must be given to catchment hydrology and land use practices, present and future. Uncontrolled land clearing and overgrazing in the catchment area will accelerate soil erosion and reduce the lifetime of reservoirs and conveyance works. In the time of the Burmese kings, strict laws were enforced so that no person, on pain of death, was permitted to cut the jungle or clear land for any purpose within 2 miles of a stream. Since such harsh laws have become obsolete, land in the Burma catchment has been cleared and erosion has accelerated to such an extent that the situation is one of the utmost gravity.

The multidisciplinary nature of projects, and thus the need in the initial stage of planning for integrated surveys, should be evident. Most problems likely to be encountered are well known to the specialist, but too often there is a communication gap between him and the planner, decision-maker, legislator, executor and user. Hazards likely to rise through delay in implementing one aspect of the project should be clearly elucidated so that the often fragile and complex equilibrium of the environment may be protected.

### *The Concept and Teaching of Design*

To me irrigation system design is a game like putting a puzzle together. The purpose of system design is to develop assemblages of individual components that will fit together to make a workable and optimized irrigation system for a specific site. The components include: hardware items such as pipes and pumps; building materials such as concrete and steel; processes such as trenching and leveling; and ideas such as moving sprinklers and setting syphon tubes. The *irrigation designers art* is to know the systems which are appropriate for a given site and the order in which selected components fit together to make a system. This takes experience and a multidisciplinary approach

since there are numerous system variations to select from and the site includes both the natural and social resources.

The *engineering design process* involves selection of the size and shape of components both to make the system workable and to produce the least cost and greatest gain. Both the *art* and *engineering* of irrigation systems require a clear mental image of what is to be accomplished and how the end results (i.e., the system in operation) will appear.

I cannot give my students a blueprint for the design process; but I can give suggestions that are helpful in the search for an image of the system and the engineering solution for achieving it. The solutions are all quite simple—after we have arrived at them.

The first order of business is to become acquainted with working irrigation systems; and it is surprising what can be learned by careful “looking” at both good and bad systems. Getting acquainted with the systems is important because we need the images for our art and we do not want to waste our time reinventing what has already been done. After getting the pictures in our head, we need to study how each system works and how its components are related and fitted together. With all of this in mind, we must now think about selecting, modifying, and tailoring systems for various site conditions.

Now this brings us to the site analysis and the necessity of creative data-gathering so that we can understand what pertinent physical and social resources are at hand and decide what we want to accomplish. It is here that we must visualize what we want to happen and focus on our images of the irrigation systems. At this point, the art of irrigation design comes into play as we select appropriate systems which will meet our goals and fit the available resources. What we are striving for is a “good” design and if we do not like the one we end up with first, we will just try something else. I tell my students that with care and practice they will be able to select the good designs from the bad ones until they have one they like.

I cannot explain how this last part is done except through meditation. Shook<sup>6</sup> discusses this faculty in man, writing:

<sup>6</sup>G.A. Shook, *Mysticism, Science and Revelation* (London: George Ronald, 1953) pp. 98-99.

All creative work requires some kind of meditation. It is practiced by the scientist in discovering new theories, new concepts and new laws. . . . The inventor also uses meditation. . . .

One begins by thinking in the usual way, or more correctly in the unusual way. That is, we start by concentrating upon the problem or concept with which we are concerned. . . . We consider all the facts that may have some bearing upon the concept, then we may find it advisable to diminish the mental activity in order to obtain a more comprehensive view of the concept. That is, we pass from the stage of concentration to the stage of meditation. It is in this subjective stage, this stage of abstraction, that new ideas, new relationships seem to emerge. Naturally there is some oscillating between the two stages and usually we pass from one to the other by imperceptible steps. Ordinarily one is hardly conscious that there is any boundary between the two stages.

Shook ends his discussion of meditation related to creative work with the following quote from 'Abdu 'l-Bahá, the Exemplar of the Bahá'í faith:

The meditative faculty is akin to a mirror; if you put before it earthly objects, it will reflect them. Therefore, if the spirit of man is contemplating earthly objects he will become informed of them. . . . This faculty brings forth from the invisible plane the sciences and arts. Through the meditative faculty inventions are made possible, colossal undertakings are carried out. . . .

Pirsig<sup>7</sup> puts the ideas expressed by Shook in a more homespun, down-to-earth way; I will try to paraphrase him as though he were talking about irrigation system design instead of motorcycle maintenance: When we first approach a design we are stuck, but this stuckness and a blank mind precede inventiveness. Stuckness should not be avoided because the harder you try to hold on to it, the faster your mind will naturally and freely

<sup>7</sup>R.M. Pirsig, *Zen and the Art of Motorcycle Maintenance* (New York: Bantam Books, 1974).



move toward finding a good design. Just concentrate on what you want to accomplish—live with it for a while. Study it like you study a line when fishing and before long, you will get a little nibble, a system design idea asking in a timid way if you are interested.

Once we have the image of our system we are ready to apply our more classical, structured, dualistic subject-object knowledge. Here is where the engineering techniques come to play, as we endeavor to structure the system so it will work the best way possible. Doing this involves the two basic categories of engineering problem solving which Rubenstein<sup>8</sup> has nicely defined:

Problem solving can be viewed as a matter of appropriate selection. When we are asked to estimate the number of marbles in a jar, we go through a process of selecting an appropriate number. When asked to name an object, we must select the appropriate word. In performing an arithmetic operation as simple as  $8 \times 7$ , we must select from our store of numbers the appropriate one.

We can distinguish two basic categories of problems. One consists of a statement of an initial state and a desired goal in which the major effort is the selection of a solution process to the desired explicit goal, but for which the process as a whole (i.e., the complete pattern of the solution) is new to us, although the individual steps are not. In such a case, we verify the acceptability of the solution by trying various processes for a solution and eliminating progressively (reducing to zero) the misfit between the desired goal and the results obtained from the trial processes. This kind of problem may be considered as a problem of design or *synthesis* in which a complete solution process is synthesized from smaller steps.

The second type of problem focuses more on the application of known transformation processes to achieve a goal. The goal may not be recognized as the correct solution immediately, but can be verified by the process in such a way that no misfit exists between the conditions

<sup>8</sup>M.F. Rubenstein, *Patterns of Problem Solving* (Englewood Cliffs, New Jersey: Prentice-Hall, Inc., 1975), pp. 6-7.

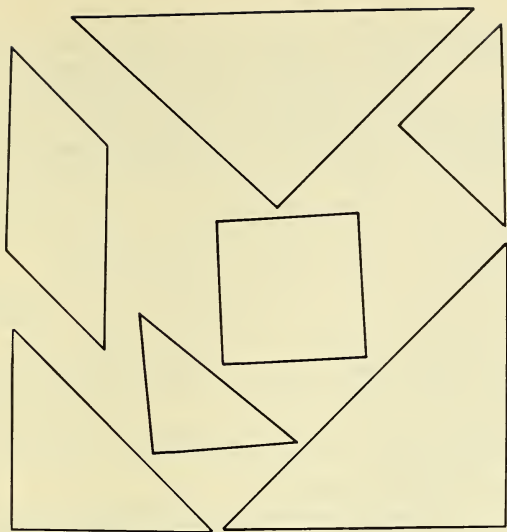
of the problem (initial state) and the solution. This kind of problem may be considered as a problem of *analysis* in which the solution consists of a transformation or change in representation of given information so as to make transparent the obscure or hidden.

The design of an irrigation system is a synthesis problem, while determining the friction loss in a pipeline is an analysis problem. Most of the engineering curriculum is concentrated on analysis. The program begins with basic science courses followed by the engineering science and analysis courses. By the time we reach the more complex problems of design or synthesis both students and professors are conditioned to think most problems can be solved with nice neat formulas which will produce "correct" answers.

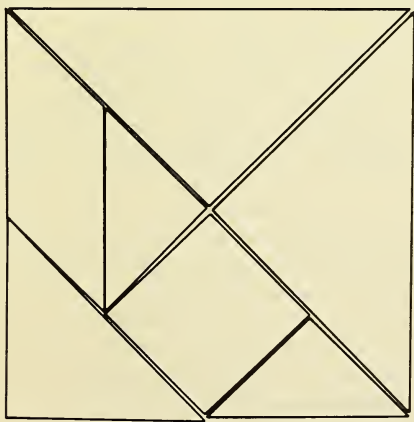
In class I try to get my students into a better frame of mind for designing systems by handing them a tangram puzzle, Figure 1, and asking them to assemble the pieces to make a square, Figure 2. I also ask them to record their thought processes, as they go along, and write me a two-page essay telling how they went about working the puzzle.

The heart of the engineering technique can best be described as a design synthesis process to achieve an objective end goal. Preliminary designs are examined via a means-ends analysis by subjecting them to a model of the environment that is most representative of the one in which the real system will operate, and noting how close the system behavior fits the goal behavior. The detection of misfits leads to modifications of the components and possibly to complete changes in the system. Once an acceptable system is synthesized, alternate acceptable models are conceived. From these feasible systems, one is selected as "best" in terms of some criteria such as least cost or maximum production.

Successful designers avoid getting set on any prescribed procedure, they explore many routes, maintain an "open mind" and a flexibility to abandon and return to various routes. Once the total picture of the system in operation has been formed, the most important guide in the search for a design solution is to work backwards. I teach my students to begin with the crop to be irrigated and design the system back to the water supply.



*Figure 1. Unassembled tangram*



*Figure 2. Tangram assembled to make a square*

## *Energy and Irrigation*

In view of the energy crunch a discussion of energy in irrigation is in order. To develop a better perspective I will relate energy to agriculture in the United States. First, we will compare the energy input required for the irrigation systems discussed earlier. Then we will consider the relationship between irrigation and other inputs for the production of a crop like field corn; and finally we will look at how the production energy input compares to the additional energy input in consuming the corn.

Modern irrigation evolved during an era of low energy costs and in areas where energy supplies were plentiful. Consequently, little attention was given to total energy input until recently. With increasing energy costs, an awareness of total energy flows has become essential; the industry of irrigated agriculture has already taken steps to reduce energy input so it can compete with rainfed agriculture. This is especially important when viewing the total world food production.

It is obvious that different types of irrigation systems may require vastly different energy input. The simple diversion of a small natural stream into suitable terrain may involve only minimal amounts of human muscle energy; while a system which pumps water from a deep well through an elaborate distribution setup composed of tons of plastic, steel, or concrete involves large energy input.

Table 2 was developed to compare the total annual energy input required by the various irrigation systems. The values in the table are given as the equivalent gallons of diesel fuel per-acre-per-year, needed to apply 24 inches of water to the crop. Values are given for the energy required to install the system divided by the life expectancy of the system, the human energy input which is only significant for the traditional method, and the pumping energy. The two values for pumping energy are for: zero lift when the water source is at the field surface, and a lift of 500 feet when it is from a deep well. In converting diesel fuel into mechanical energy, an energy conversion efficiency of 25 percent was assumed. Thus to supply the 2000 kcal per day of food energy required by a working man would be equivalent to about 1/3 gallon of diesel fuel in Table 2.

Figure 3 is a graphical presentation of the total energy required for the various systems over a range of water lifts from

TABLE 2. *Total annual energy inputs to various irrigation systems in equivalent gallons of diesel per acre to apply 24 inches of net irrigation water.*

Irrigation System <sup>1</sup>	Installation <sup>2</sup>	Labor	Pumping <sup>3</sup>		Total Energy	
			Zero	500 ft	Zero	500 ft
Traditional	?	20	0	396	20	416
Hand-move Sprinkle	17	1	58	285	76	303
Center-Pivot Sprinkle	42	1	51	249	94	292
Trickle	57	1	41	217	99	275

<sup>1</sup>All of the systems occupy a 160 ac (1/2-x 1/2-mile) square field with the water supply in one corner.

The traditional system is surface irrigated and has an assumed efficiency of 40%.

The hand-move sprinkle system utilizes low-pressure sprinklers and has an assumed system inlet pressure of 56 psi and efficiency of 70%.

The center-pivot system is a standard 1/4-mile lateral fitted with low-pressure sprinklers and has an assumed inlet pressure of 56 psi and efficiency of 80%.

The trickle system has an assumed inlet pressure of 50 psi and efficiency of 90%.

<sup>2</sup>Taken from J.C. Batty, S. N. Hamad, and J. Keller, "Energy Inputs to Irrigation," *Journal of the Irrigation and Drainage Division, ASCE*, 101, 4 (1975): 293-307.

$$^3\text{Pumping energy} = \frac{79.2 \times \text{Inches applied} \times \text{Total feet of head}}{\text{Pumping efficiency} \times \text{irrigation efficiency}}$$

For this table the pump efficiency was assumed to be 60 percent.

zero to 500 feet. It is interesting to note that all four systems require about the same amount of energy for a water lift of 200 feet; and the order of energy preference reverses as the lift increases from less than 200 feet to over 200 feet. For example, the traditional surface method requires the least energy at zero lift and the most at 500 feet of lift. The reason the lines cross in Figure 3 is that the systems have different efficiencies. The efficiencies assumed were 40, 70, 80, and 90 percent for the traditional, hand-move, center-pivot and trickle systems, respectively.

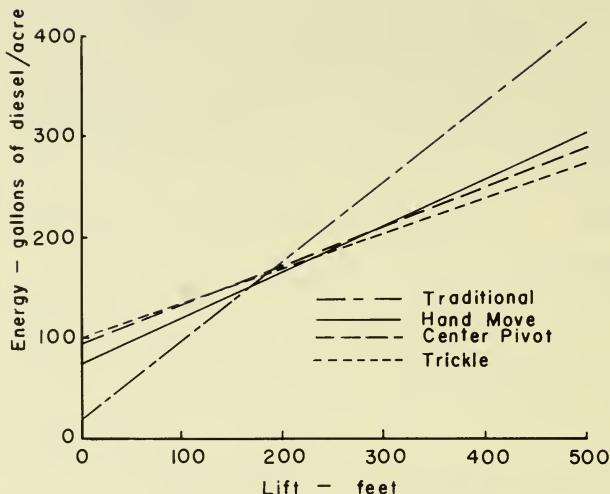


Figure 3. *Total annual energy inputs required by different irrigation systems as a function of water lift. Based on 24 inches of net irrigation per year.*

Energy required to manufacture the aluminum, plastic and steel for the sophisticated systems causes the installation energy to be high. This loses its importance as the pumping energy increases with the lift. The pumping energy at zero lift is needed to pressurize the sprinkle and trickle systems.

I developed Table 3 to point out the energy relationship between rainfed and irrigated agriculture and the relative amount of energy required for irrigation as compared to the other production inputs for field corn. It was assumed 24 inches of net irrigation is needed and the pumping lift was 200 feet (that is where the lines cross on Figure 3). Table 3 gives the various energy values in both kcal per acre and as a percentage of the totals.

That irrigated agriculture with high pumping lifts is energy intensive is apparent in Table 3. However, if the lift were zero the energy input for the four systems would be:

Irrigation Method	kcal/lb of corn
Traditional	590
Handmove sprinkle	855
Center-pivot sprinkle	940
Trickle	965
Rainfed	607

Thus, for traditional irrigation systems with zero or low lifts, the energy cost for producing corn is even lower than for rainfed agriculture in the United States. However, for the more sophisticated systems, the energy costs are considerably higher than for corn production under rainfed agriculture.

TABLE 3. *Estimated energy used per acre to produce dry field corn under rainfed and irrigated conditions in the United States.*

Item	Rainfed <sup>1</sup>		Irrigated <sup>2</sup>	
	Kcal <sup>3</sup> per ac	% of Total	Kcal per ac	% of Total
Labor	5	0.2	10	0.1
Machinery	410	15.2	420	4.1
Diesel	800	29.0	1000	9.8
Fertilizer	1060	38.5	1870	18.4
Seed	65	2.4	100	1.0
Pesticides	25	0.9	40	0.4
Harvest & Handling	380	13.8	450	4.4
Irrigation	—	—	6300	61.8
Totals	2755	100	10190	100
Yield	81 bu/ac		140 bu/ac	
Energy Input	607 kcal/lb		1300 kcal/lb	

<sup>1</sup>Based on D. Pimental, "Food Production and the Energy Crisis," *Science* 182 (November 1973):443-449.

<sup>2</sup>Authors estimates for increased inputs to get increased yields. Taking data from Figure 3 for any system with a 200-foot pumping lift the total annual irrigation energy required is 170 gallons of diesel per acre (or 6300 thousand Kcal per acre).

<sup>3</sup>Kcal = 1000 kcal.

Brown and Batty<sup>9</sup> decided to take a look at the energy flow in the United States food system. To get a feel for it they tracked

<sup>9</sup>S.J. Brown and J.C. Batty, "Energy and Our Food System: A Microscale View," *Transactions of ASAE* 19,4(1976): 758-761.



the energy inputs into a single Number 303, 1-pound, can of whole kernel corn from production to consumption. A can of corn, which has a digestable energy content of 269 kcal, was selected because its production was already well documented, and it is a world wide staple. Figure 4 summarizes their findings. The differences in the energy input for producing whole kernel corn for canning and the dried field corn of Table 3 are readily explainable; the yield is different for moist and dry corn, and there is no standard value which can be used for the irrigation lift or system type. Anyhow, these minor differences are insignificant compared to the total energy input to corn in our food system. The energy input involved in producing and consuming a can of nonirrigated whole corn is equivalent to about 1/10 gallon of diesel; for irrigated corn it is about 1/7 gallon which is more than a pint of diesel and would not even fit in the empty corn can.

The rising costs of the high energy input for irrigation has stimulated greater interest in: improving both pump and water application efficiencies; optimizing system design to reduce operating pressure requirements; more careful scheduling of irrigation; and new innovative low energy irrigation practice. These energy conservation practices are essential for many irrigated farms in the United States to stay in business. Obviously, the first to go out of business have been and will continue to be those with high water lifts, low efficiencies, and low crop value. Energy conserving irrigation practices are even more important in developing nations with more limited fuel reserves and foreign exchange restrictions.

### *Holistic Thinking and Innovative Technologies*

In my teaching and engineering activities I am involved with people from many parts of the world who have varying backgrounds and interests. The selection and appropriateness of irrigation technologies is usually in view but seldom in clear focus because the question of appropriateness involves many fields of thought such as faith, philosophy, economics, finance, politics, history, expediency, science, and engineering.

Schumacher<sup>10</sup> has suggested a technology with a human face, and emphasizes appropriate and intermediate technologies. In general, I am in agreement with Schumacher

<sup>10</sup>E.F. Schumacher, *Small is Beautiful* (London: Bland and Brigg, 1973), pp. 136-149.



<u>Agriculture</u> non-irrigated 450 kcal/can		<u>Agriculture</u> pumped irrigation 1175 kcal/can
<u>Processing</u> 655 kcal/can		<u>Processing</u> 655 kcal/can
<u>Packaging</u> 1105 kcal/can		<u>Packaging</u> 1105 kcal/can
<u>Transportation</u> 441 mile haul 231 kcal/can		<u>Transportation</u> 1000 mile haul 477 kcal/can
<u>Marketing</u> 340 kcal/can		<u>Marketing</u> 340 kcal/can
<u>Shopping</u> 2 ½ mile round trip 654 kcal/can		<u>Shopping</u> 5 mile round trip 982 kcal/can
<u>Home Preparation</u> 1 dishwasher cycle per day 430 kcal/can		<u>Home Preparation</u> 2 dishwasher cycles per day 650 kcal/can
<hr/> Total 3865 kcal/can		<hr/> Total 5384 kcal/can

*Figure 4. Summary of energy input (kcal) to a one-pound can of whole kernel corn. The left column shows energy input based on conservative assumptions. The right column shows how these energy inputs can vary depending on the assumptions made.*

but I am concerned that in using the words "intermediate," "appropriate," and "technology" we are in danger of limiting our perspectives or understanding. "Intermediate" for instance should not merely suggest an "oil drum" technology but should rather include every level up to just below western technology. The question of what is or is not appropriate varies from country to country while the scale of the technology is a third variable. It is important, therefore, to spend time in a country assimilating its standards and culture, in order to identify what really is appropriate.

The various irrigation systems have evolved in a regional sense in such a manner that the social, political, and management needs of each type of system have been taken for granted. Whatever the system, the primary function of irrigation is to provide water to the rootzone in proper quantities at appropriate times; the crux of this deceptively simple statement is the words "proper" and "appropriate." The objective, however, is to utilize available water resources effectively for crop production without detriment to other social or economic goals.

Whereas irrigation principles are reasonably well understood and universally applicable, their use is strongly specific to the situation. Generally, the use must match physical, social and economic factors on the farm and also find a compromise among objectives within a societal framework. Sometimes, technological and management options are at hand; at other times, innovative or new methods must be devised.

Historically, irrigation project development throughout the world has seldom produced the returns envisioned by planners. This is especially true with projects in developing countries involving peasant farmers; and one often hears that the projects and farm irrigation systems were properly selected and beautifully designed; but the "people" failed to make them work!

In short, one would be hard-pressed to find many projects which come close to reaching the projected time schedule. This problem arises, in part at least, from the belief that a good physical irrigation system is synonymous with good irrigation, when it is very easy to have poor or essentially no irrigation even with a good system, and it is even possible to have good irrigation with a poor system.

I believe it is this confusion between the physical irrigation system and the activity of irrigation that leads to the disappoint-

ing results in irrigation project implementation. The activity of irrigation is often taken too much for granted once the physical system has been developed. In the United States this problem may not be serious. We are familiar with the overall system, so we tend to develop irrigation techniques which are congruent with existing levels of technology and farmer practices.

This situation does not exist with relation to peasant farms in developing countries, and other factors must be taken into account. For one, where labor intensive agriculture is practiced, it may not be appropriate to replace the irrigator with machines, and in such cases, planners must select irrigation techniques which have a reasonable chance of being productive without abruptly replacing labor with capital intensive machinery. In addition, the training needed for successful operation and maintenance of the system *must be incorporated into the development procedure.*

In order to achieve these results, the social context within which development is to occur has to be taken into account. Adams, et al<sup>11</sup> suggests that the best way to do this is to involve the farmers in the planning process. This can promote project success in several ways. First, it provides the developers with better insight into peasant agricultural needs and concerns. At the same time, it allows planners to tap the knowledge the farmers have developed through many years of experience in the project area. Their involvement can also increase their commitment to new practices and alter community organization. Finally, it can be used to create sufficient understanding of the project for peasant farmers to make further improvements as needed.

Much of the technology which is being promoted to improve the effectiveness of irrigation through the world was instigated in the developed nations. This technology reflects the energy and monetary economics as well as the type of people in the areas where it originated. Often alternate technologies, which would be better suited for developing nations, have been bypassed, rejected, or are too little advertised and known; and sometimes, it may be advantageous to mix simple technologies with more advanced ones.

<sup>11</sup>N. Adams, J. Keller, and B.M. Spillman, "Peasant Involvement in On-Farm Irrigation Development," *Proceedings, ASCE Specialty Conference, Blacksburg, Virginia, July 26-28*, pp. 813-826.

Last fall while on an assignment for the Ford Foundation in India, I had the opportunity to recommend both alternate and mixed technologies. The main task was to distribute equitably the water available, and to irrigate efficiently groups of tiny (1/10 to 1 acre) farms supplied from small rain catchment reservoirs. The appropriate irrigation technology appeared to be simple hose fed sprinklers operating at low pressure. This is certainly not an unusual concept, for perhaps we have one million acres of kitchen gardens and home lawns irrigated this way in the United States; however, such systems are seldom recommended and, in fact, most designers are not even aware of them as possibilities for farm use. David Miller, one of our students took leave fall quarter and supervised the installation of the system.

The mixed technology we innovated is a hand-move sprinkle system using conventional equipment but moved in a circular center-pivot fashion. This concept occurred to me while presenting a series of slide lectures covering some of the latest irrigation techniques used in the United States. During my travels it became obvious, and for good reason I might add, that India is not a machine-oriented society and our latest irrigation techniques are not appropriate there. While pointing this out I made the plea that the concepts be received with an open mind in hopes of stimulating the discovery of new Indian irrigation technologies—and this led to the hand-move center-pivot.

Wiener<sup>12</sup> has stressed that engineering is not the fundamental problem underlying irrigation development in the less developed countries. Engineering principles are the same the world over and can, with minor modifications, be transferred from developed to less developed countries. Rather, the problem is to engender a transformation in the farmer, in his expectations and motivations, in the agricultural production process in all its aspects—techniques and inputs—and in the institutional framework at the village and regional level. Whereas this transformation in the developed countries evolves spontaneously, this is not the case in the less developed countries, and is certainly not true of the small traditional farmer sector, and hence development models from the developed countries cannot be transferred to the less developed countries.

<sup>12</sup>A. Wiener, "The World Food Situation and Irrigation Programmes," *ICID Bulletin* (January 1976):21-25, 34.

In ending I would like to leave you with the thought expressed so well by Pirsig:<sup>13</sup>

The way to solve the conflict between human values and technological needs is not to run away from technology. That's impossible. The way to resolve the conflict is to break down the barriers of dualistic thought that prevent a real understanding of what technology is—not an exploitation of nature, but a fusion of nature and the human spirit into a new kind of creation that transcends both. . .

With optimistic vision I see the Sun is slowly rising, bringing a brighter tomorrow; and though progress is painfully slow, I sense a feeble but relentless momentum toward a universal concern for all mankind—so I truly believe in Irrigating for Rainbows.

<sup>13</sup>R.M. Pirsig, *Zen and the Art of Motorcycle Maintenance* (New York: William Morrow and Co., Inc., Bantam Books, 1974), p. 284.



***Blue eyes twinkling  
Smile a face full  
Mind cranking creative  
Living large  
To the very end***

***With optimistic vision I see the Sun is slowly rising,  
bringing a brighter tomorrow; and though progress is  
painfully slow, I sense a feeble but relentless momentum  
toward a universal concern for all mankind—so I truly  
believe in Irrigating for Rainbows.***

Jack Keller, 61<sup>st</sup> Faculty Honor Lecture,  
Utah State University, 1980

*In Loving Memory Of*  
***Jack Keller***

*Entered Into Life*  
January 5, 1928  
Roanoke, Virginia

*Entered Eternal Life*  
November 10, 2013  
Denver, Colorado

*Graveside Services*  
Mountain View Memorial Park  
Boulder, Colorado  
Saturday, November 16, 2013  
Two o'clock in the Afternoon

*Welcoming*  
Andy

*Contributions by family*  
Jeff and others

*Baha'i prayer for mankind*  
Judith and Nelson

*Baha'i prayer for the departed*  
Lauren

*Pallbearers*

Ian  
Malayna  
Erica  
Avery

Antonia  
Maria  
Max  
Zayk

*Arrangements entrusted to Crist Mortuary*









